Tritium:
A MicroPower Source for On-Chip Applications

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Outline

- Tritium: Basics
- Tritium: A MicroPower Source
  - Beta-Voltaics
  - Beta-Powered MEMS
  - Beta-Luminescence
  - Cold Electron Source
- Tritium: A Characterization/Diagnostic Tool
  - Tritium Tracer Studies
  - Tritium Effusion Studies
  - Defect Dynamics
  - Particle Sensor Applications

- Summary
Tritium

- Isotope of Hydrogen

- $^3\text{H} \rightarrow ^3\text{He}^+ + \beta^- + \bar{\nu}_e + 18.6 \text{ keV}$

- Nuclear Half-life: $t_{\frac{1}{2}} = 12.32 \text{ years}$
  $\lambda = 1.78 \times 10^{-9} \text{ s}^{-1}$

- Activities: $1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$
  $1 \text{ Ci} = 0.39 \text{ std cc}$
  $1 \text{ Ci} = 33.7 \mu\text{W}$

- Biological: Half-life: 10 days
  ALI*: 80 mCi
  *Annual Limit on Intake

- Chemically: Identical to $^1\text{H}$
  Mass effect (~3amu)
  Beta catalysis

- Range (max): 4.5 – 6 mm in air
  5 – 7 micron in water
Producers & Users

Producers of Tritium
- Ontario Power Generation (OPG)
  - ~1 kg/year
- Korean Electric Power Company (KEPCO)
- USA
  - 225 kg produced since 1955
  - 12-75 kg stockpiled
- Russia
- India, Pakistan

Users of Tritium
- Pharmaceutical Research (~100g)
- Tritium Lighting Industry (~30g)
- Fusion Studies
  - Magnetic Confinement (ITER ~40g)
  - Inertial Confinement
- Other

1 Tritium Unit (TU) = 1 T : $10^{18}$ H
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- Summary
BetaVoltaics

- **1951, Ehrenberg, Lang, & West:**
  - Electron-voltaic effect (on a Se device)

- **1956, Rappaport**
  - First direct conversion betavoltaic device (planar configuration, 0.4% efficiency)

- **1968, Klein**
  - Band-gap dependence of electron-hole pair ($ehp$) generation by ionizing radiation

- **1974, Olsen**
  - Theoretical treatment of betavoltaic conversion efficiencies for a variety of semiconductor materials

- **1970s, D W Douglas Laboratories**
  - Planar silicon betavoltaics fueled with $^{147}$Pm
  - Efficiencies ranged in 0.7 to 2%
Renewed Interest in Radioisotope Batteries

- Continual miniaturization of electronic and electromechanical systems
  - Decreased power consumption

- Integrated Power Sources (SoC)

- High energy densities compared to chemical batteries

- Operation in extreme environments
  - For example, temperatures of -100 to +150 °C
MicroPower Applications

Sensor/Memory Chips
Power requirement: 1-10 μW
- Non-volatile Memory
- RF-ID tag
- Electrostatic actuation of MEMS/NEMS

SoC Microsystem
Power requirement: 1-10 mW
- Chip-scale atomic clock
- Micro-gas Analyzer
- Chip-scale Navigation system
Market

- All Batteries: $50 billion

- Target markets for betavoltaic batteries
  - Oil, gas, and environmental
  - Military
  - Medical
  - Space
  - Emerging MEMS/NEMS

- Market for betavoltaics $1 billion +
Electron/Beta Voltaics

**Band Diagram**

- **Metal Contact**
- **Energetic Electrons**
- **Depletion Region**
- **$n$-Si**
- **$p$-Si**

**$ehp$: electron-hole pair**
## Choice of Radioisotope

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$E_{\text{avg}}$ (keV)</th>
<th>$E_{\text{max}}$ (keV)</th>
<th>$P$ (W/g)</th>
<th>Work (kWh/4y/g)</th>
<th>$T_{1/2}$ (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H-3</td>
<td>5.7</td>
<td>18.6</td>
<td>0.34</td>
<td>10.3</td>
<td>12.3</td>
</tr>
<tr>
<td>Ni-63</td>
<td>21</td>
<td>66</td>
<td>0.07</td>
<td>2.5</td>
<td>92</td>
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<tr>
<td>Sr-90</td>
<td>540</td>
<td>900</td>
<td>0.75</td>
<td>25</td>
<td>28</td>
</tr>
<tr>
<td>Pm-147</td>
<td>62</td>
<td>230</td>
<td>0.34</td>
<td>7.3</td>
<td>2.6</td>
</tr>
</tbody>
</table>

### Tritium
- Low energy $\beta$- emitter (benign radioisotope)
- Low cost: $2.5$-$4$/Ci
- Long enough lifetime
- Can be immobilized in a solid matrix
- On-chip integration
- Mature (existing tritium lighting industry)
Intrinsic Tritiated Amorphous Silicon Betavoltaic Device

- Substitute tritium for hydrogen in hydrogenated amorphous silicon pin photovoltaic devices

- Tritium within the energy conversion layer
  - In contrast to betas originating from a source external to the device

- Volume source battery
  - Attained through stacking of many cells
  - In contrast to a planar surface source battery

Tritiated Intrinsic Layer (uniform)

a-Si:T Betavoltaic Device

\[ \text{At } t \sim 0 \]
\[ I_{sc} = 0.98 \text{ nA} \]
\[ V_{oc} = 21 \text{ mV} \]
\[ \eta = 0.1\% \]

\[ \text{At } t \sim 10 \text{ days} \]
\[ I_{sc} < 0.1 \text{ nA} \]

a-SiH Betavoltaic Cell Powered by $T_2$ Gas

**a-SiH Betavoltaics**

*with ultrathin contact*

- Cr, 5nm
- $p$-a-Si:H, 20 nm
- $i$-a-Si:H, 450 nm, 10-15 % H
- $n$-a-Si:H
- SS substrate

Tritium gas

*pressure: 678 torr*

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**At $t \sim 0$**

- $I_{sc} = 637$ nA/cm²
- $V_{oc} = 457$ mV
- $\eta = 1.2\%$

**At $t \sim 46$ days**

- $\eta < 0.1\%$

Porous Silicon 3D Betavoltaics

- Introduce micropores in silicon through electrochemical anodization
- Create $pn$ junction in the pores through diffusion of n-type dopant
- Introduce an appropriate radionuclide in the pores
- A Volume Source Battery

3D Versus 2D Betavoltaics


\[ \eta_{2D} = 0.02\% \]
\[ \eta_{3D} = 0.2\% \]
### III-V Betavoltaics

#### AlGaAs/GaAs Heterojunction Betavoltaics


<table>
<thead>
<tr>
<th>Source of betas</th>
<th>Generated current density $\mu A/cm^2$</th>
<th>Open circuit Voltage, V</th>
<th>Output Power, $\mu W/cm^2$</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tritium-titanium</td>
<td>0.04</td>
<td>0.75</td>
<td>0.024</td>
<td>5.6</td>
</tr>
<tr>
<td>Tritium gas</td>
<td>0.76</td>
<td>0.91</td>
<td>0.55</td>
<td>5.8</td>
</tr>
<tr>
<td>Tritium green lamp</td>
<td>0.12</td>
<td>0.78</td>
<td>0.074</td>
<td>---</td>
</tr>
</tbody>
</table>
Silicon Carbide Betavoltaics

4H SiC BV Cell

1 mCi, $^{63}$Ni Source (66keV)

- $I_{sc} = 16.8$ nA/cm$^2$
- $V_{oc} = 0.72$ V
- $\eta = 6\%$

Ni

$n$ SiC, 0.25 μm, $^7$N doped

$p$ SiC, 4 μm

$p^+$ SiC

Al/Ti

4H SiC $\text{pin BV Cell}$

8.5 GBq, $^{33}$P Source (249 keV)

- $I_{sc} = 2.1$ μA/cm$^2$
- $V_{oc} = 2.04$ V
- $\eta = 4.5\%$

Ni/Au

$p$ SiC

$i$ SiC

$n$ SiC

Ni/Au


Contact Potential Difference Betavoltaics

Air-medium CPD BV

$I_{sc} = 2.7 \, nA/cm^2$

$V_{oc} = 0.5 \, V$

Solid CPD BV

$I_{sc} = 5.3 \, nA/cm^2$

$V_{oc} = 0.16 \, V$

Liu, Chen, Kherani, Zukotynski, Antoniazzi, 
MEMS: Radioisotope-Powered Piezoelectric Generator

- Self-reciprocating direct-charging cantilever

- Direct conversion of collected-charge-to-motion energy into electrical
  - Radioisotope kinetic energy stored in the cantilever
  - Piezoelectric generator converts stored mechanical energy into electrical energy

- Overall efficiency 2.78%

BetaLuminescence

- 1898, Becquerel
  - Radioluminescence
  - Phosphorescence material: potassium uranyl sulphate

- 1920s, Elster, Geitel, and Cookers
  - Alpha radiation induced scintillations in ZnS.

- 1967, International Atomic Energy Agency (IAEA)
  - Standards for the use of common RL sources.
  - Most common: tritium beta-luminescence

- Present
  - Tritium gas lighting
  - Radium ZnS:Cu paint
  - Novel materials & technologies in Betaluminescence
    - Organic
      - all-organic formulation: polystyrene and fluorescent dye
      - organic system with inorganic phosphor
    - Inorganic
      - semiconductor pn junctions
      - incorporation of tritium in solid matrix:
        amorphous materials, hydrides, carbon nanotubes, zeolites
Cold Electron Source

- Tritium immobilized in a solid
- Materials
  - Tritiated metal tritides
  - Tritiated amorphous silicon
    - Plasma enhanced chemical vapour deposition: entire film
    - Tritiation post film deposition: ~50 nm
  - Tritiated silica on Si-chip
    - High pressure tritium loading
    - Laser irradiated locked tritium
  - Tritiated silicon
    - High pressure tritium loading
    - Surface region: ~ 10 nm
  - Tritiated carbon nanotubes
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Tritium Tracer Technique

- Tritium as a tracer in measurement of hydrogen permeation in polymer for selection of new material in hydrogen fuel cell.
- Two diagnostics to trace permeating HT: an ionization chamber tritium detector and an HTO water trap/copper oxide furnace/HTO water trap system.
- Tritium radiotracer method: simple, effective, reliable.

Stodilka, Kherani, Shmayda, Thorpe,
Tritium Tracer Technique (cont’d)

- Materials Tested: EPDM, Teflon, Viton, Santoprene, and Noryl

- Permeation Parameters in reasonable agreement with referenced values of H, D, T

Characteristic permeation curve for Noryl at 60 °C

Arrhenius plot of tritium permeation for the five polymers


<table>
<thead>
<tr>
<th>Polymer</th>
<th>Temperature (°C)</th>
<th>$P_0^b$</th>
<th>$E_p^c$</th>
<th>$D_0^b$</th>
<th>$E_d^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viton</td>
<td>63–129</td>
<td>$1.72 \times 10^{-4}$</td>
<td>47.7</td>
<td>$2.22 \times 10^{-5}$</td>
<td>29.1</td>
</tr>
<tr>
<td>Teflon</td>
<td>74–150</td>
<td>$8.38 \times 10^{-9}$</td>
<td>16.7</td>
<td>$1.39 \times 10^{-7}$</td>
<td>14.9</td>
</tr>
<tr>
<td>EPDM</td>
<td>44–76</td>
<td>$2.74 \times 10^{-7}$</td>
<td>24.4</td>
<td>$3.50 \times 10^{-5}$</td>
<td>27.9</td>
</tr>
<tr>
<td>Santoprene</td>
<td>20–60</td>
<td>$1.21 \times 10^{-6}$</td>
<td>25.1</td>
<td>$1.36 \times 10^{-5}$</td>
<td>21.2</td>
</tr>
<tr>
<td>Noryl</td>
<td>18–70</td>
<td>$2.11 \times 10^{-9}$</td>
<td>12.3</td>
<td>$4.05 \times 10^{-7}$</td>
<td>16.9</td>
</tr>
</tbody>
</table>
Tritium Outgassing Studies

- A tool to study hydrogen stability in materials

- High sensitivity
  - Difficult-undetectable for the inactive H-isotope using conventional methods

- Dry and wet test
  - Absorption of HTO desorbed from surface of a given sample

- Tritiated amorphous silicon at room temperature
  - Atomic T concentration: 9%
  - Asymptotic evolution: $2 \times 10^8 \text{atm cm}^{-2} \text{s}^{-1}$
  - Equivalently: Void-Network H diffusion half-life of 60 years
  - This is for a low H stability material, owing to the high void fraction of the material

Tritium Effusion Monitor
Tritium Effusion

- Tritiated amorphous silicon
  - No tritium evolution at room temperature
  - Characteristic peaks observed at temperatures above the film growth temperature
    - Lower temp peak: higher hydrides SiHₓ
    - Higher temp peak: mono-hydride SiH

- Tritiated carbon nanotubes
  - Tritium exposure:
    - 100 bar at 100 °C for 3 days
  - Concentration:
    - Atomic: 1.9%
    - Weight: 0.5%
  - Gaussian deconvolution:
    - Peaks at 240 °C and 500 °C
    - High temp peak: chemisorbed T
    - Low temp peak: physisorbed T

Defect Dynamics

- Hydrogenated amorphous silicon solar cells
  - Staebler-Wronski effect
  - Formation of Si-dangling bonds upon light exposure
  - Drop in efficiency

- Tritiated amorphous silicon
  - Defined rate of tritium decay, hence formation of Si-dangling bonds
  - Can study samples under defined conditions (no light exposure)

- Dynamic defect model

Beta Source Particle-Smoke Detector

- Tritium beta source instead of traditional alpha source
  - No gamma emission (as in Am-Be alpha source)
  - Provides bipolar and unipolar regions in the detector
  - Higher absolute current signal
  - Higher sensitivity
    - Several to forty fold more responsive than alpha based detectors
    - Functions like a dual detector (ionization and photoelectric detectors)
  - Smouldering fires
  - Open flame fires

Summary

- Tritium a micro-power source
  - Radio-Isotope Micropower Sources (RIMS) is an active area of R&D
  - Renewed interest is motivated by continual miniaturization of electronic and electromechanical devices with concurrent reduction in power requirements
  - Tritium an amenable radioisotope given its properties and availability

- Tritium a powerful diagnostic for hydrogen-material studies
  - Ease of experimentation given hydrogen is pervasive
  - Unparalleled sensitivity under “non-vacuum” conditions
  - Fundamental studies
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